

4<sup>th</sup> POWER CONVERTERS FOR PARTICLE ACCELERATORS WORKSHOP

# SIRIUS POWER SUPPLIES

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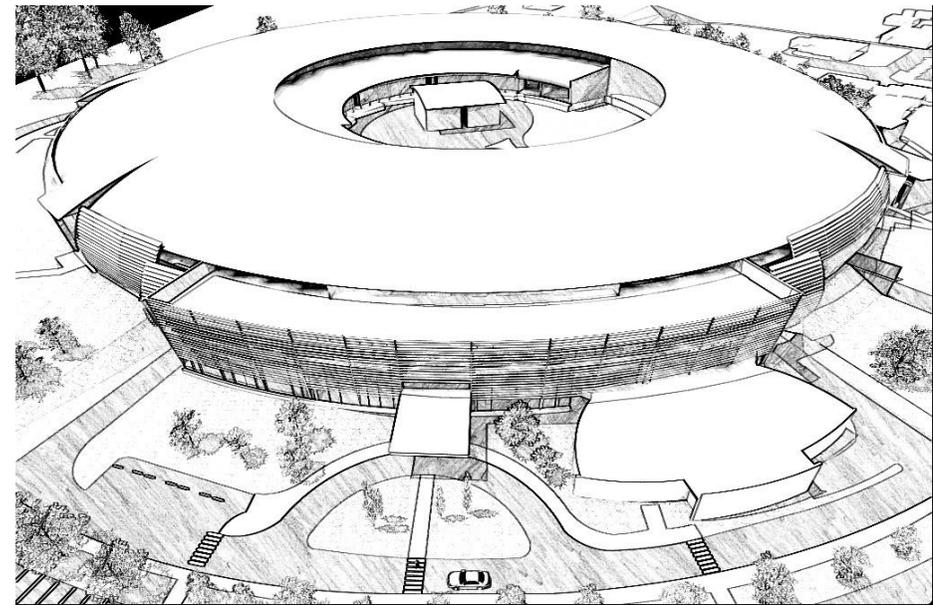
ELP - Power Electronics Group

LNLS – BRAZILIAN SYNCHROTRON LIGHT LABORATORY  
CNPq – NATIONAL CENTER OF RESEARCH IN MATERIALS AND ENERGY

SEPTEMBER/2014

# OUTLINE

- **THE SIRIUS PROJECT**
- **POWER SUPPLIES REQUIREMENTS**
- **PS TOPOLOGIES**
- **DIGITAL REGULATION SYSTEM**
- **RESULTS**



## GENERAL ASPECTS

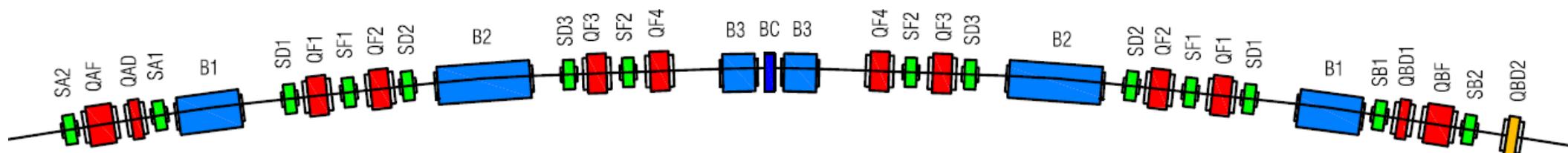
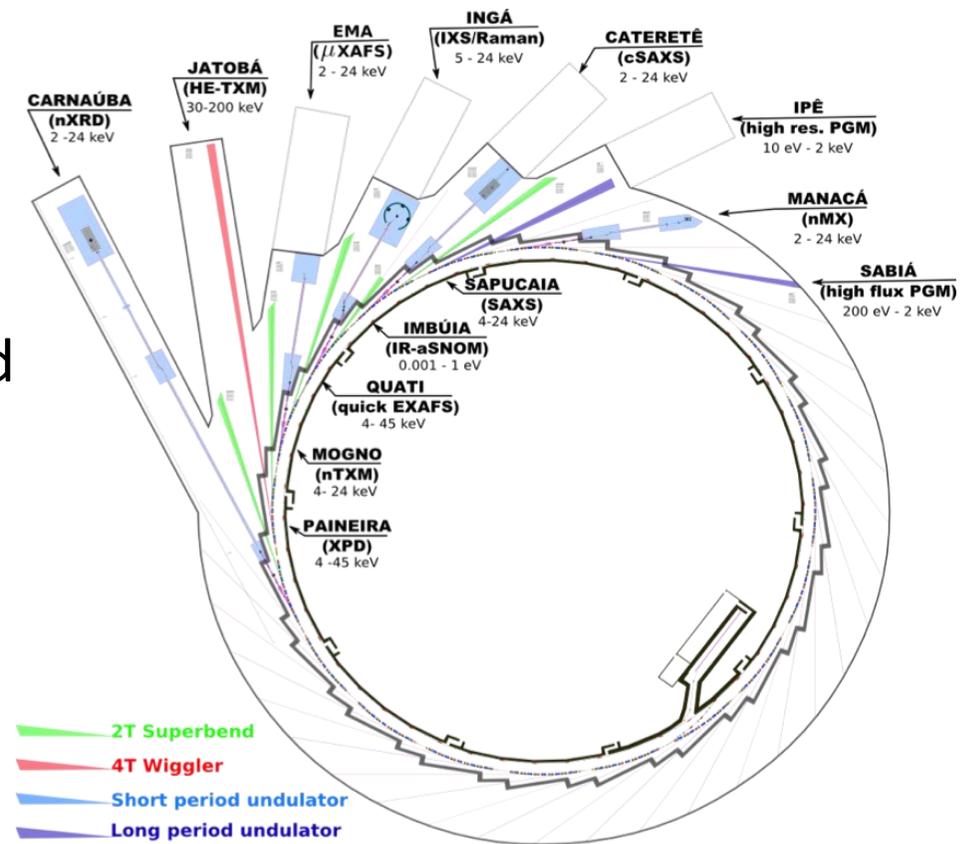
- New Brazilian Synchrotron Light Source, operated by LNLS
- 3<sup>rd</sup> generation machine, located in Campinas - SP



# THE SIRIUS PROJECT

## TECHNICAL ASPECTS

- **Electrons energy: 3 GeV**
- **Circumference: 518 m**
- **Ultra-low emittance: 280 pm.rad**
- **Max. current: 500 mA**
- **RF freq: 500 MHz**
- **13 Beamlines (first budget)**



## DEVELOPMENT AND CONSTRUCTION STATUS

- Earthmoving complete
- Most of subsystems conceptual designs have been tested
  
- **First beam: 2018**



## STORAGE RING POWER SUPPLIES REQUIREMENTS

PARAMETER	DIPOLE			QUAD MAIN COILS			SEXT MAIN COILS		STEERING MAGNET		SKEW QUAD	QUAD TRIM COILS			SEXT TRIM COILS	
	B2	B1	B3	QxF	QFx	QAD1 QBDx	SAx SBx	SDx SFx	Horiz	Vertic		QxF	QFx	QAD1 QBDx	SAx SBx	SDx SFx
Magnets/PS	<u>20</u>	<u>20</u>	<u>20</u>	20	<u>40</u>	20	20	40	1	1	1	1	1	1	1	1
<b>PS Quantity</b>	<b><u>2</u></b>			<b><u>2</u></b>	<b><u>4</u></b>	<b><u>3</u></b>	<b><u>4</u></b>	<b><u>5</u></b>	<b><u>160</u></b>	<b><u>120</u></b>	<b><u>80</u></b>	<b><u>40</u></b>	<b><u>160</u></b>	<b><u>60</u></b>	<b><u>80</u></b>	<b><u>200</u></b>
PS Quadrant Number	1Q			1Q	1Q	1Q	1Q	1Q	4Q	4Q	4Q	4Q	4Q	4Q	4Q	4Q
Load Inductance [mH]	<u>344</u>			640	<u>960</u>	240	220	440	1.5	1.5	0.5	-	-	-	-	-
Load Resistance [mΩ]	<u>1265</u>			1449	<u>2089</u>	<u>829</u>	<u>849</u>	<u>1449</u>	197	197	167	-	-	-	-	-
<b>Nominal Current [A]</b>	<b><u>300</u></b>			<b><u>100</u></b>	<b><u>100</u></b>	<b><u>100</u></b>	<b><u>100</u></b>	<b><u>100</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>
<b>Nominal Voltage [V]</b>	<b><u>400</u></b>			<b><u>150</u></b>	<b><u>210</u></b>	<b><u>90</u></b>	<b><u>90</u></b>	<b><u>150</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>	<b><u>10</u></b>
Nominal Power [kW]	<u>120</u>			<u>15</u>	<u>21</u>	<u>9</u>	<u>9</u>	<u>15</u>	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ripple <sup>(1)</sup> [ppm]	20			20	20	20	20	20	50	50	50	-	-	-	-	-
12-h Stability [ppm]	50			50	50	50	50	50	100	100	100	-	-	-	-	-

(1) RMS, Bandwidth: 10 Hz – 1 kHz

Total number of storage ring power supplies:

**920**

## BOOSTER POWER SUPPLIES REQUIREMENTS

PARAMETER	DIPOLE	QUADRUPOLE		SEXTUPOLE		STEERING MAGNET	
		QF	QD	SF	SD	Horiz	Vertic
Magnets/PS	25	50	12.5	12.5	5	1	1
<b>PS Quantity</b>	<b>2</b>	<b>1</b>	<b>2</b>	<b>2</b>	<b>2</b>	<b>25</b>	<b>25</b>
PS Quadrant Number	2Q	2Q	4Q	4Q	4Q	4Q	4Q
Load Inductance [mH]	115	450	113	168	67	3.4	3.4
Load Resistance [mΩ]	295	2275	1239	2407	2216	259	259
<b>Nominal Current [A]</b>	<b>1000</b>	<b>130</b>	<b>15</b>	<b>10</b>	<b>10</b>	<b>10</b>	<b>10</b>
<b>Nominal Voltage [V]</b>	<b>900</b>	<b>550</b>	<b>25</b>	<b>30</b>	<b>25</b>	<b>10</b>	<b>10</b>
Nominal Power [kW]	295	38	0.28	0.24	0.22	0.03	0.03
Ripple <sup>(1)</sup> [ppm]	30	30	30	50	50	50	50
12-h Stability [ppm]	100	100	100	100	100	200	200

(1) RMS, Bandwidth: 10 Hz – 1 kHz

Total number of storage ring power supplies:

**59**

## GENERAL ASPECTS

- 16-bit resolution for reference current
- “*Relative tracking error*” of 100-ppm for booster power supplies
- Control and communication functionalities:
  - 10 Mbps RS-485
  - Postmortem
  - Waveform storage
  - Synchronization inputs for ramping and FOFB
- Some specifications are still not defined (accuracy, set-point latency, bandwidth)

*Transfer line magnets are still undefined, as well as its power supplies.*

## THREE POWER SUPPLY FAMILIES

### ➤ **Low-Power (956 units)**

- 10 A or 15 A,  $P_{OUT} < 300$  W, bipolar
  - Steering magnets, skew quadrupoles, trim coils, booster sextupole and quadrupole QD

### ➤ **High-Power (20 units)**

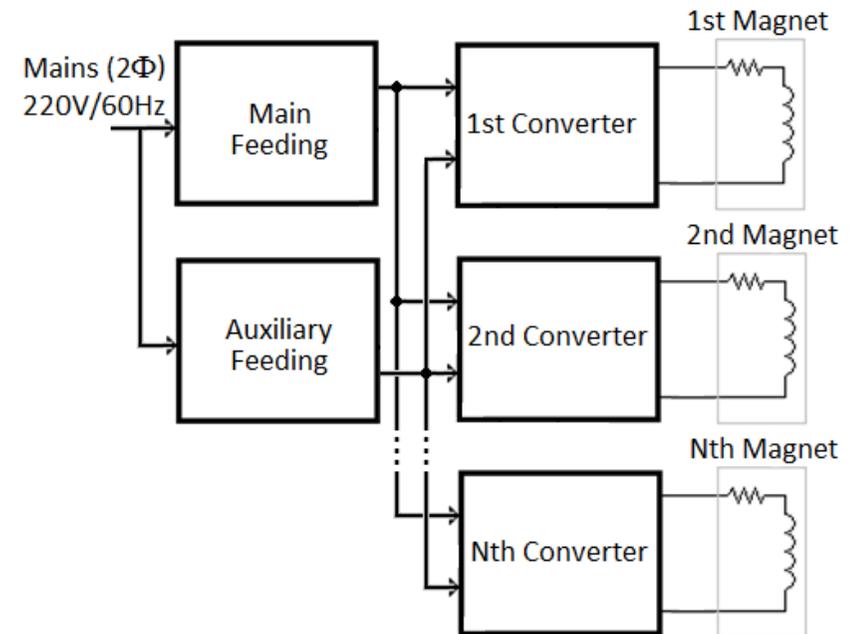
- 100 A or 300 A,  $10$  kW  $< P_{OUT} < 240$  kW, unipolar
  - Storage ring dipoles, quadrupoles and sextupoles

### ➤ **AC-Power Supplies (3 units)**

- 130 A (38 kW) or 1000 A (295 kW), 2 Hz, unipolar (I) and bipolar (V)
  - Booster dipoles and quadrupoles QF

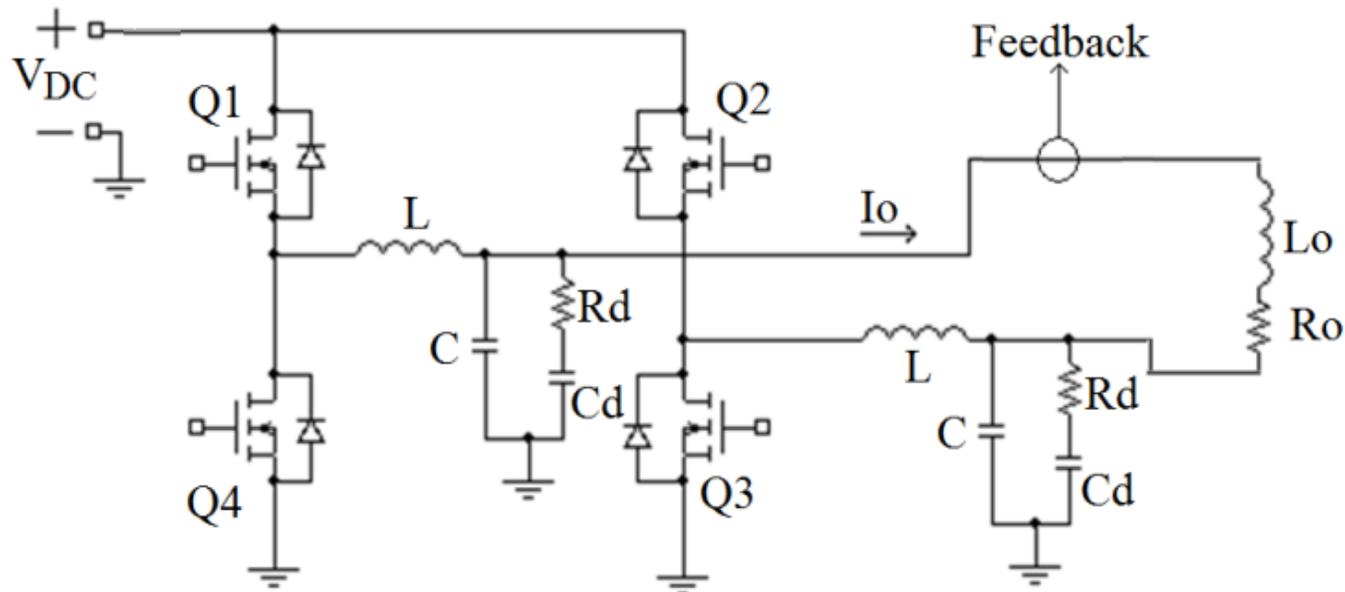
## LOW-POWER PS

- 3U-based *in-house* DC/DC modules for current sources
- Commercial AC/DC's for shared DC bus (main) and controllers supplies (auxiliary) with redundancy
- Programmable DC bus for different loads
- Low current DCCT's for feedback
- Natural cooling for 10 A and forced ventilation for 15 A



## LOW-POWER PS

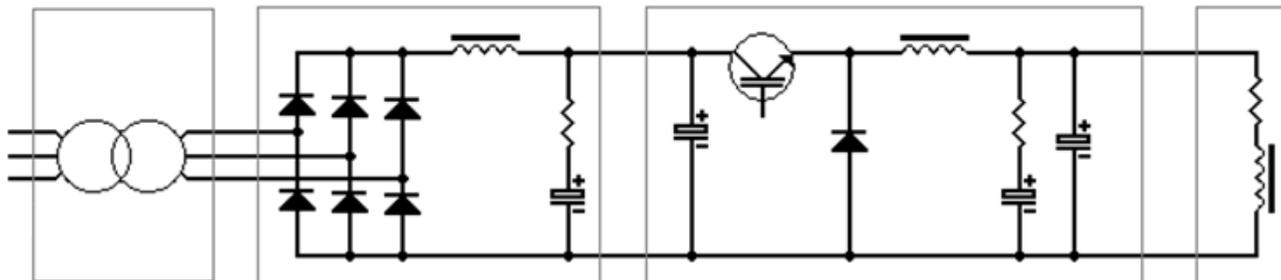
- Damped LC output filter
- Interleaved full-bridge
  - ✓ Smooth zero-crossing, with reduced output RMS
  - ✓  $f_{out} = 2f_{sw}$  (reduced ripple and transistor losses)



## HIGH-POWER PS

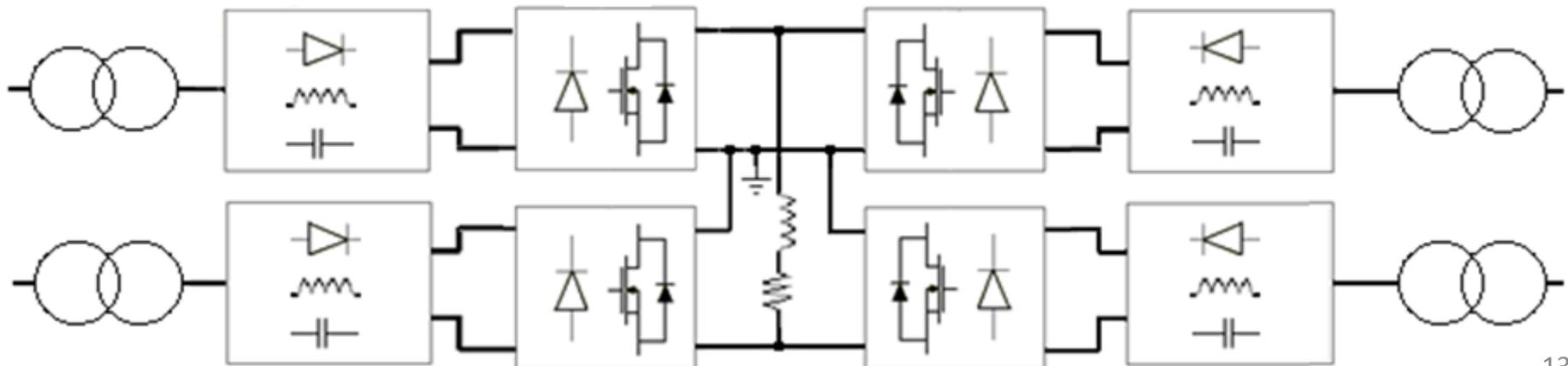
- Modular DC/DC stages (150 A / 210 V)
- Different DC bus voltages and series/parallel combinations to provide unique solution for all high-power needs
- Simplifies development, manufacturing and maintenance
- *Overspecs* components increases reliability

Magnets	Units	A / V
Quad + Sextu	7	100 A / 90 V
Quad + Sextu	7	100 A / 150 V
Quad	4	100 A / 210 V
Dipole	2	300 A / 400 V



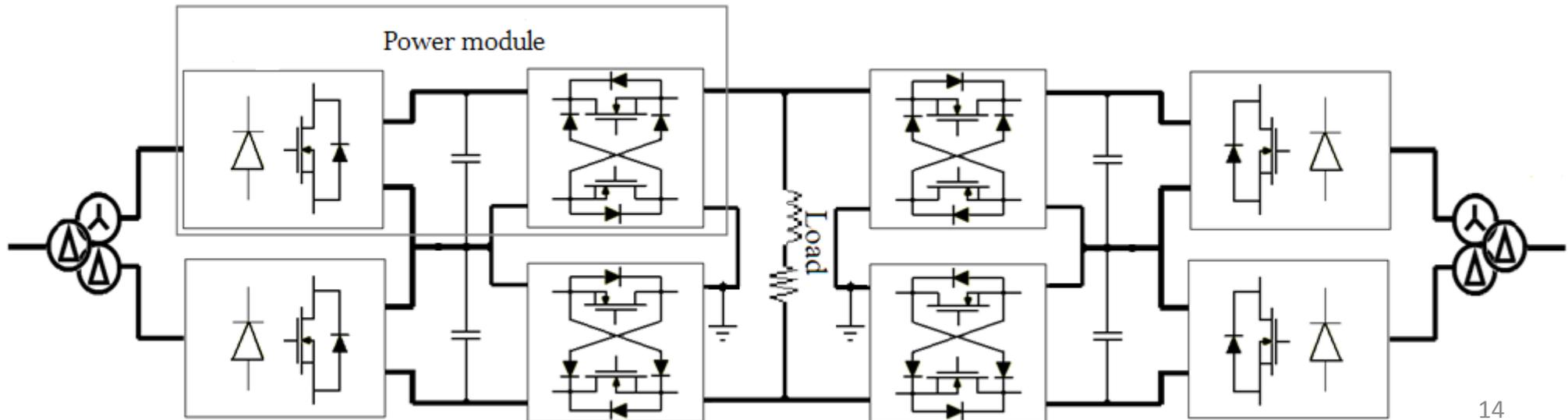
## HIGH-POWER PS - DIPOLES

- 4 switching modules in parallel + series combination
- Grounded center point (lower output voltage points)
- Interleaved switching
- Hall sensors for each module to equalize currents and DCCT for output feedback
- Input stages of parallel modules may be shared, decreasing costs and volume



## AC POWER SUPPLIES

- Similar modular concept will be applied to booster dipole power supplies
- One module for booster quadrupoles
- Large capacitor bank after input stage to decrease 2 Hz oscillation in the grid

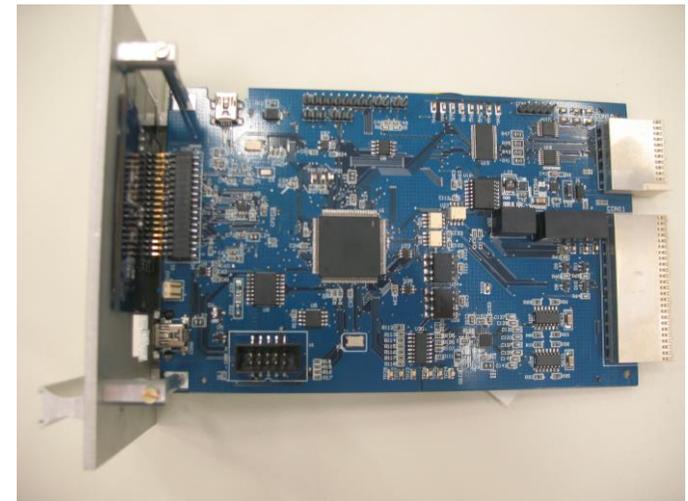


## GENERAL ASPECTS

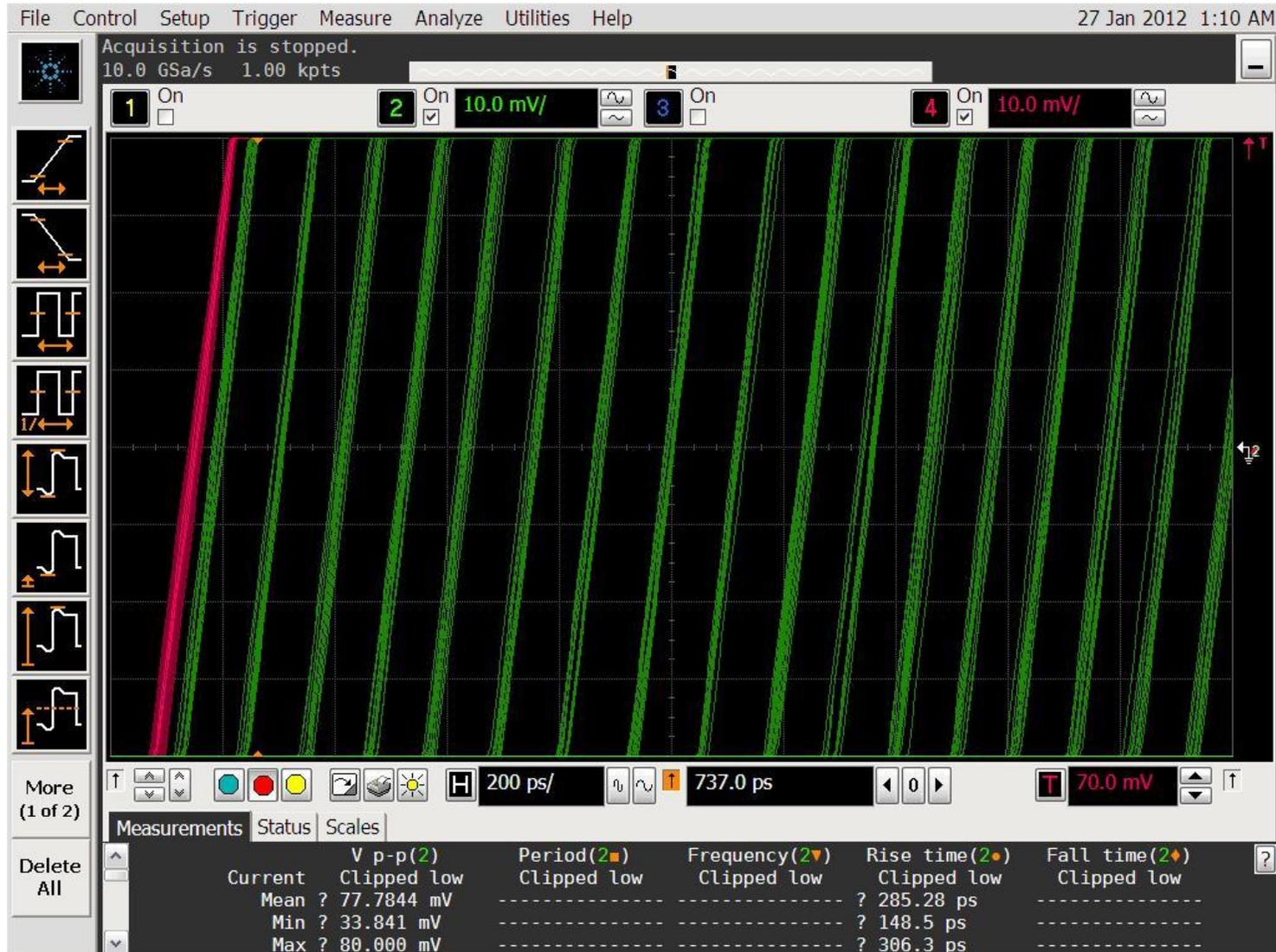
- LNLS first experience with digital regulation for power supplies
- Standard control solution for all types of PS's in Sirius
- Integrates:
  - ✓ Communication interface with higher-level system + HMI
  - ✓ Feedback measurement conditioning and digitizing
  - ✓ Control law calculation and DPWM generation
  - ✓ Auxiliary analog measurements
  - ✓ Interlocks and log events
- Dual-core ARM + DSP based solution
- First investigations were made with evaluation boards

## UDC 1<sup>ST</sup> PROTOTYPE

- ARM (75/100 MHz) + DSP (150/100 MHz)
- 10 Mbps RS-485 (control system)
- USB 2.0 (PC supervisory)
- 25 MHz SPI Interface
- 8x HRPWM (150-ps resolution)
- 8x digital inputs / 4x digital outputs (isolated)
- 8x 12-bit analog channels ( $\pm 10$  V isolated)
- Touchscreen display for local operation
- On-board Flash and SRAM memories
- Control loops up to 100 kHz

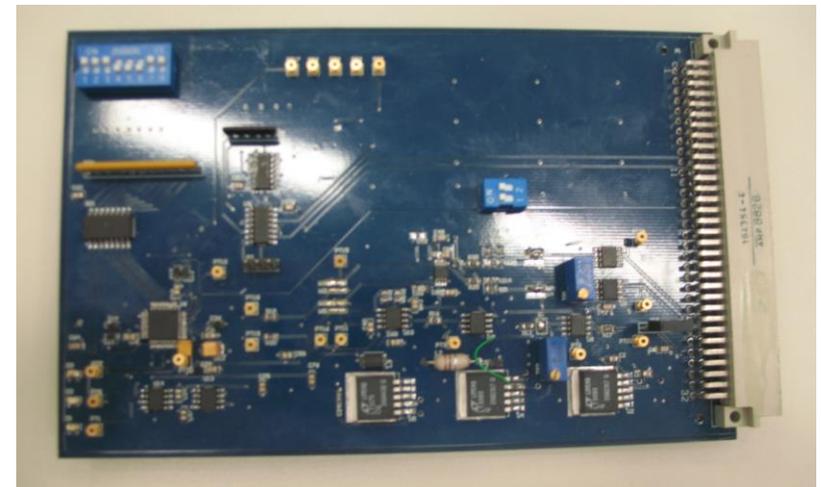


## HRPWM RESOLUTION TEST



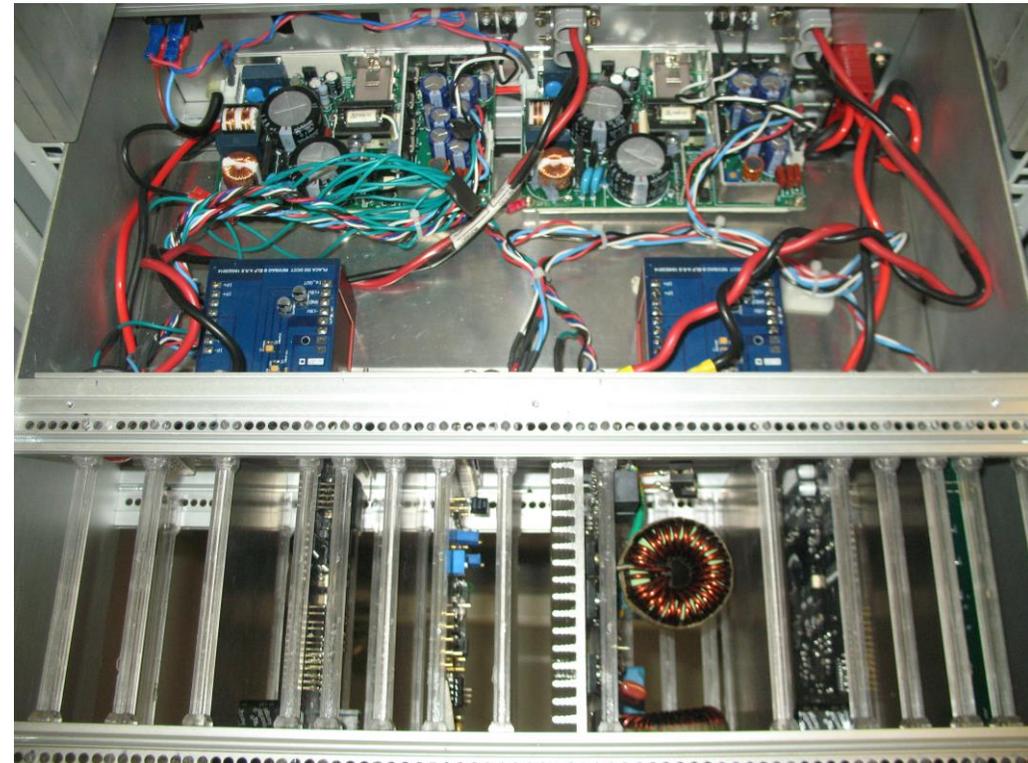
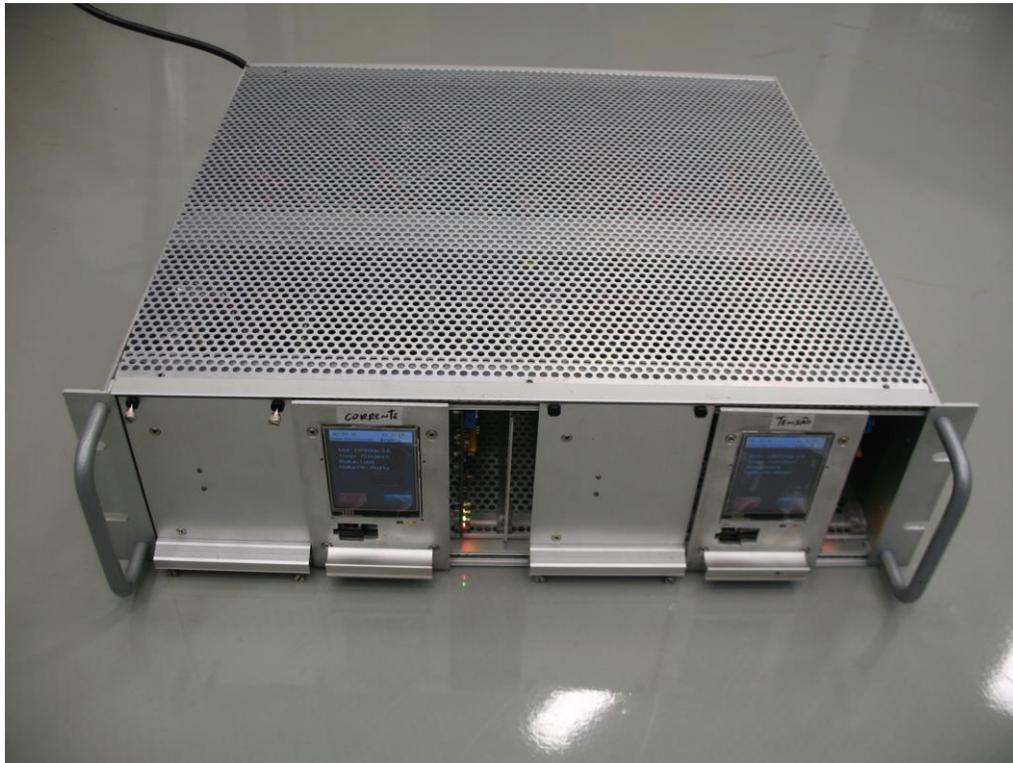
## HRADC 1<sup>ST</sup> PROTOTYPE

- 18-bit SAR ADC
- Sample rates up to 600 kSPS
- SPI Interface
- 1<sup>st</sup> and 2<sup>nd</sup> order anti-aliasing filter
- Two input modes:
  - ✓ Voltage input
    - $\pm 10$  V
    - Fully differential signal-chain
  - ✓ Current input
    - $\pm 50$  mA
    - 2 ppm/°C burden resistor



## LOW-POWER 1<sup>ST</sup> PROTOTYPE

- 2 power supplies/rack
- AC/DC for DC bus outside rack
- Natural cooling up to 100 W

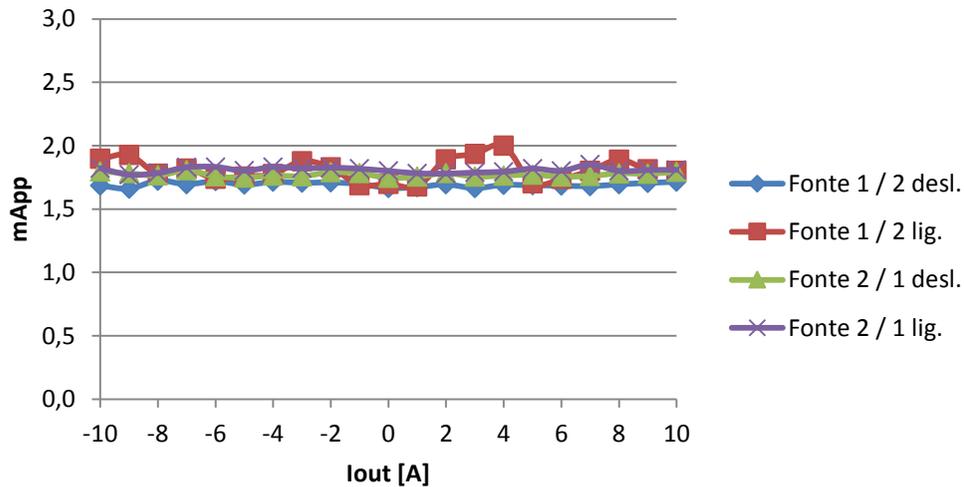


## LOW-POWER TEST CONFIGURATIONS ( $T_{AMB} = 20^{\circ}\text{C}$ )

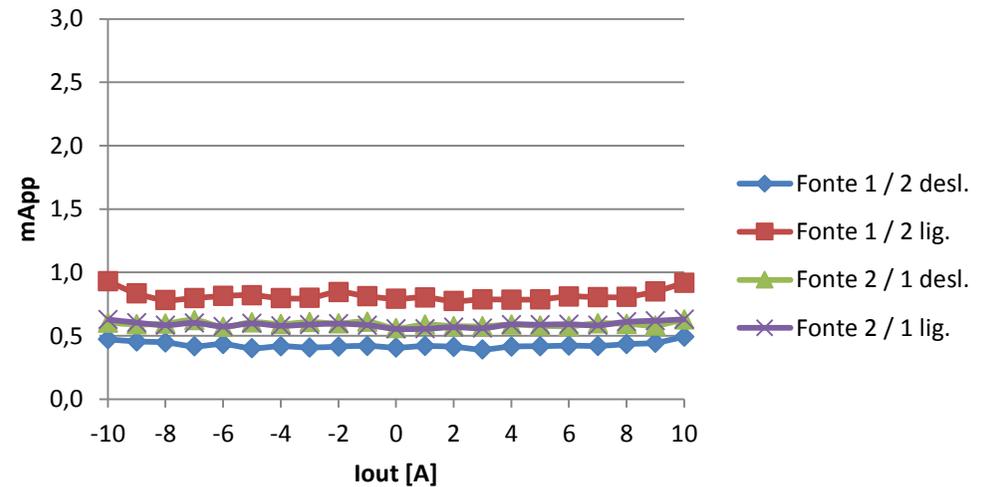
- **Condition 1:** (optimized for booster corrector magnet)
  - ✓  $R_{load} = 0.5 \Omega$
  - ✓  $L_{load} = 3.1 \text{ mH}$
  - ✓ DC-link = 8.2 V
  
- **Condition :** (100 W with booster corrector magnet )
  - ✓  $R_{load} = 1 \Omega$
  - ✓  $L_{load} = 3.1 \text{ mH}$
  - ✓ DC-link = 15 V
  
- **Condition 1:** (UVX storage ring corrector)
  - ✓  $R_{load} = 1 \Omega$
  - ✓  $L_{load} = 26 \text{ mH}$
  - ✓ DC-link = 15 V

## LOW-POWER RIPPLE (CONDITION 1)

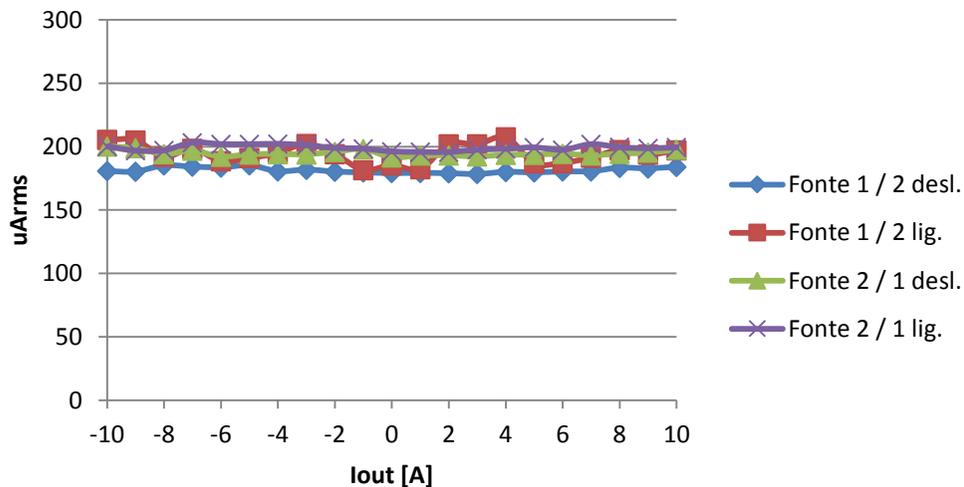
Ripple Pk-Pk @ DC - 1 MHz



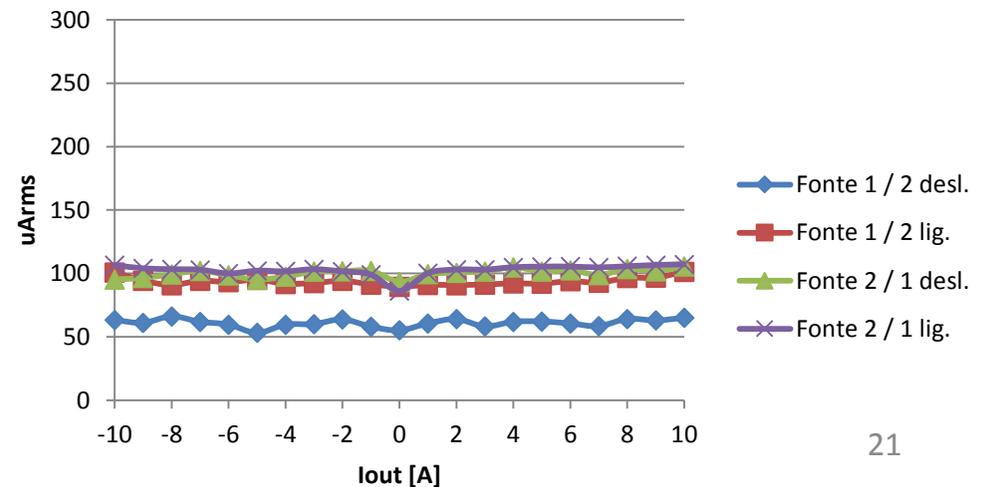
Ripple Pk-Pk @ 10 Hz - 1 kHz



Ripple RMS @ DC - 1 MHz

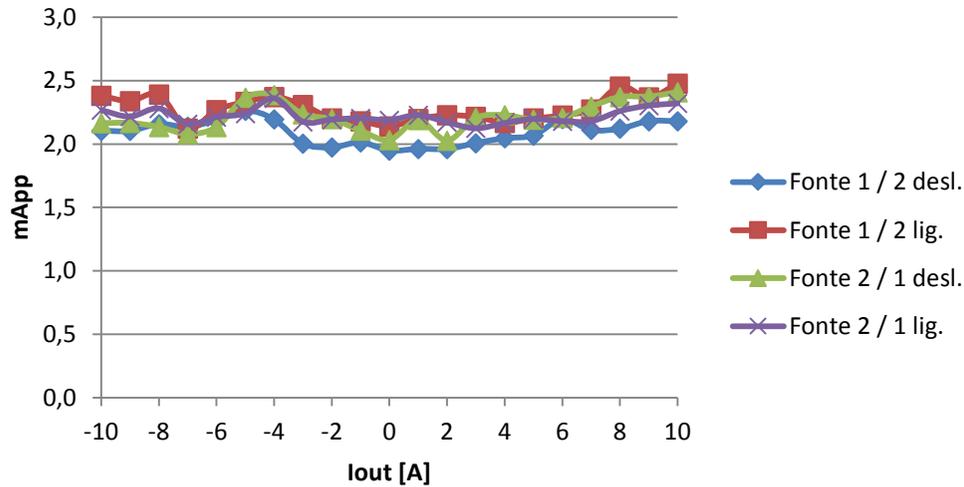


Ripple RMS @ 10 Hz - 1 kHz

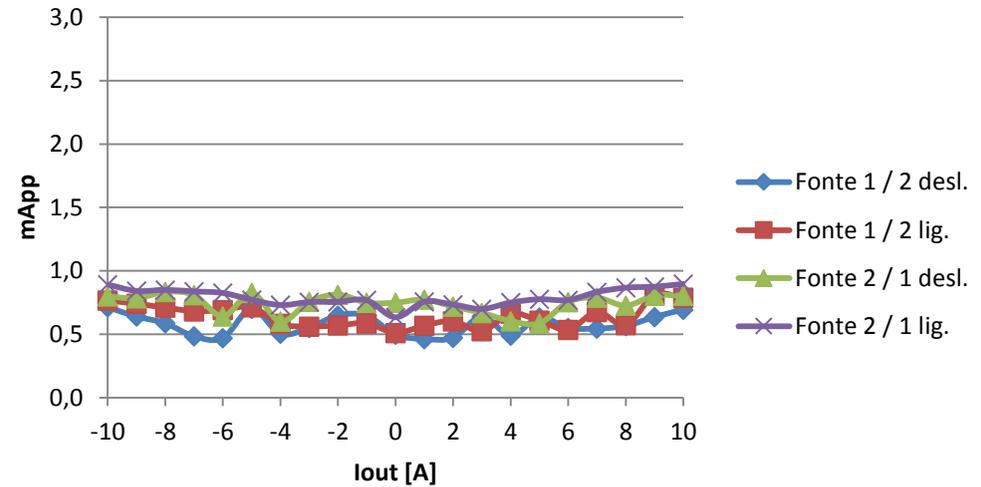


## LOW-POWER RIPPLE (CONDITION 2)

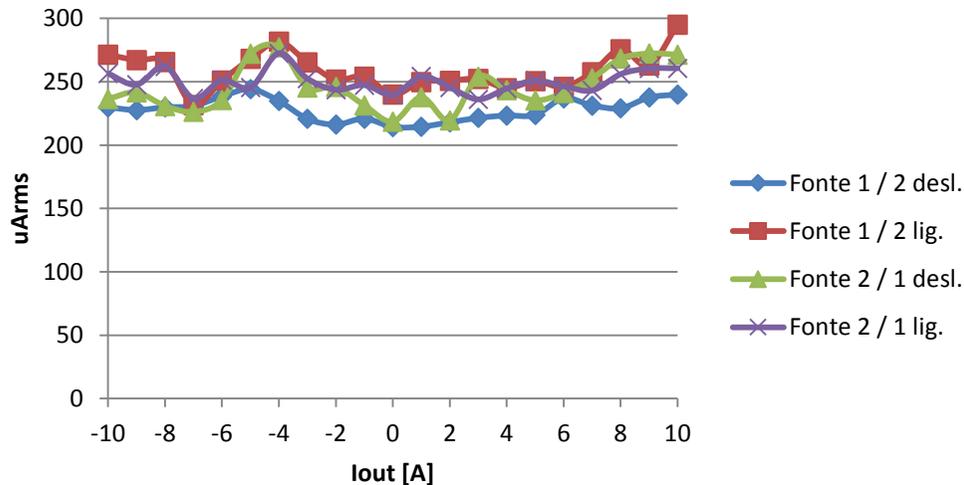
Ripple Pk-Pk @ DC - 1 MHz



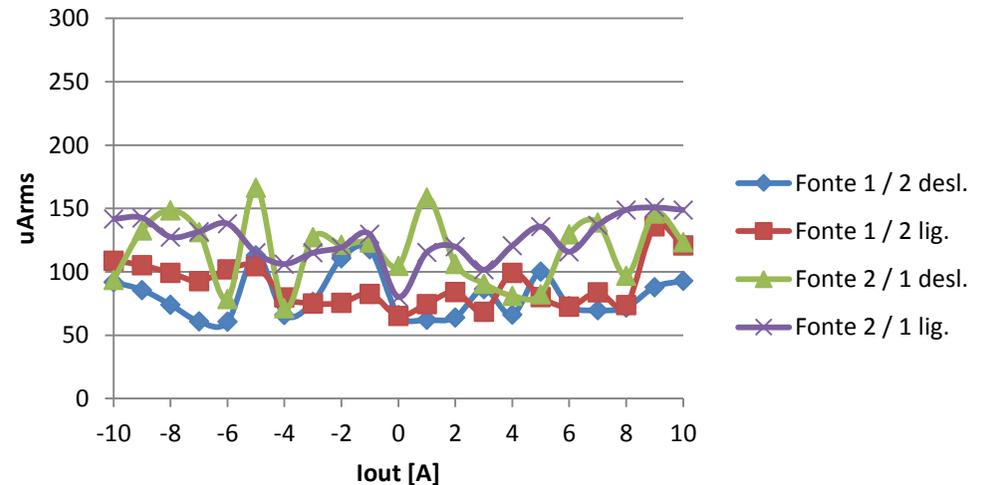
Ripple Pk-Pk @ 10 Hz - 1 kHz



Ripple RMS @ DC - 1 MHz

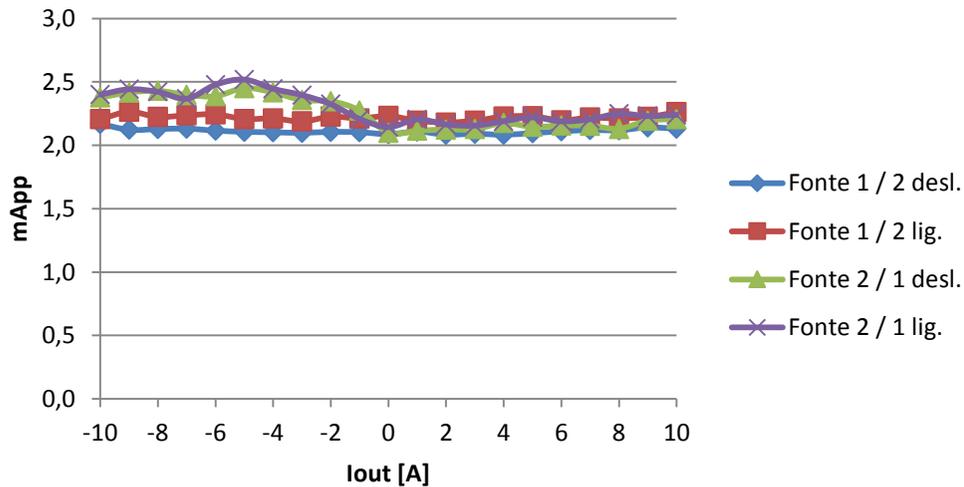


Ripple RMS @ 10 Hz - 1 kHz

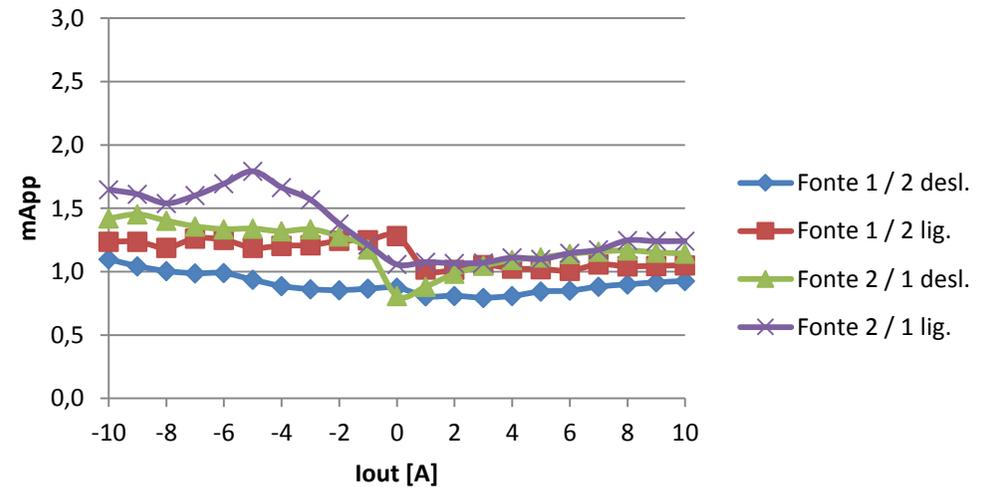


## LOW-POWER RIPPLE (CONDITION 3)

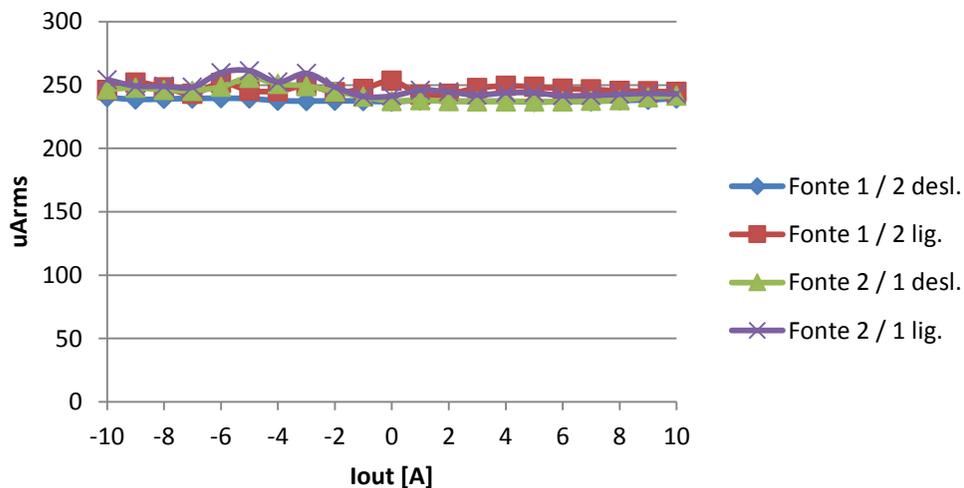
### Ripple Pk-Pk @ DC - 1 MHz



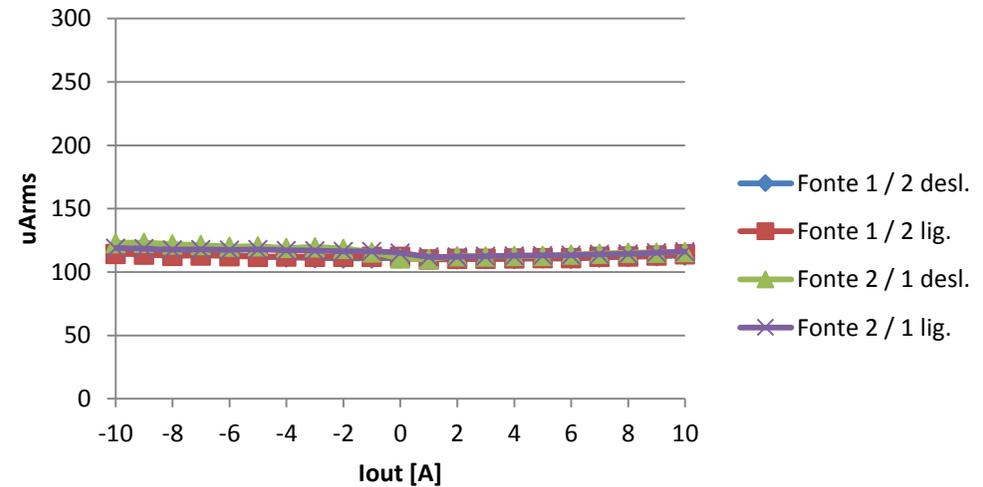
### Ripple Pk-Pk @ 10 Hz- 1 kHz



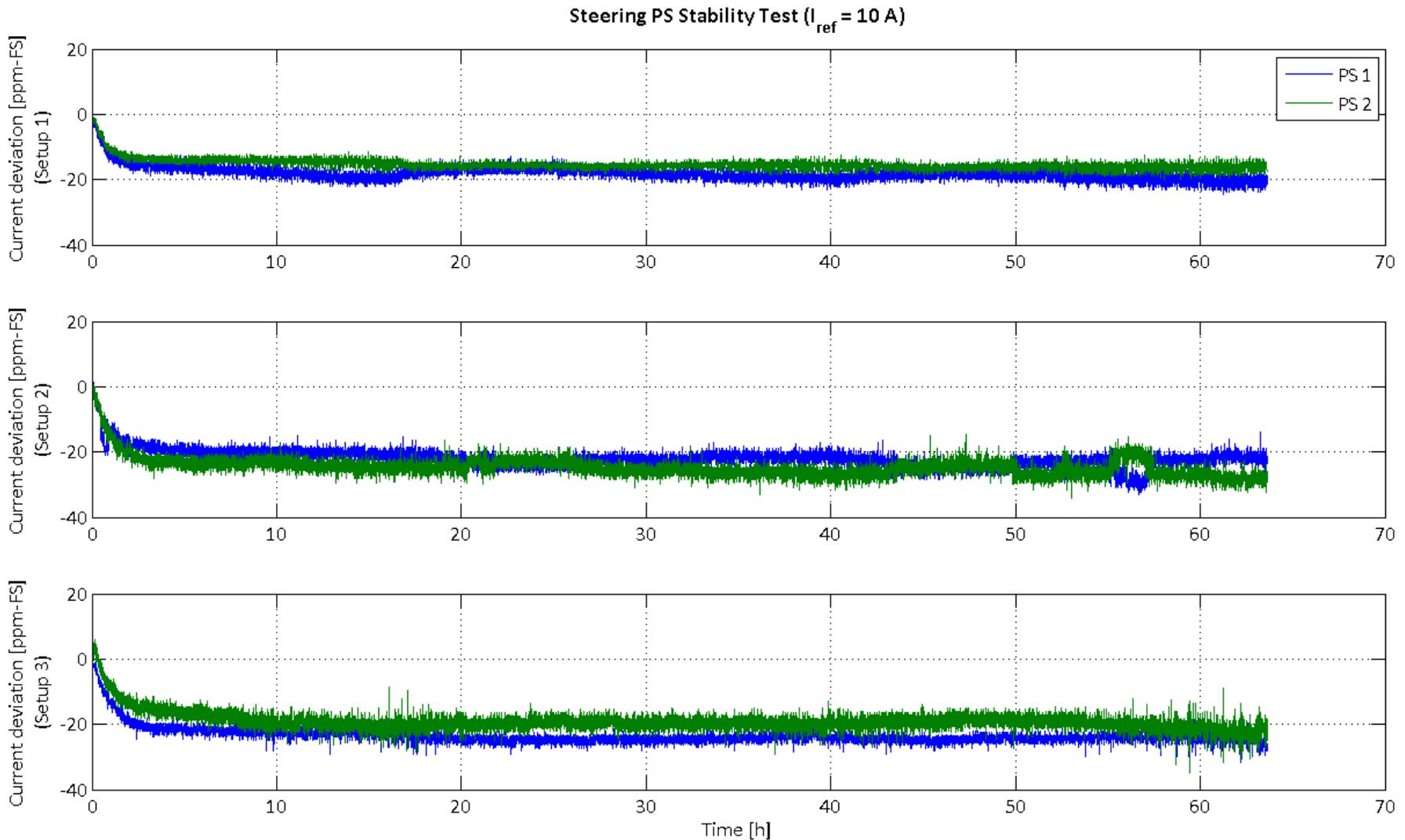
### Ripple RMS @ DC - 1 MHz



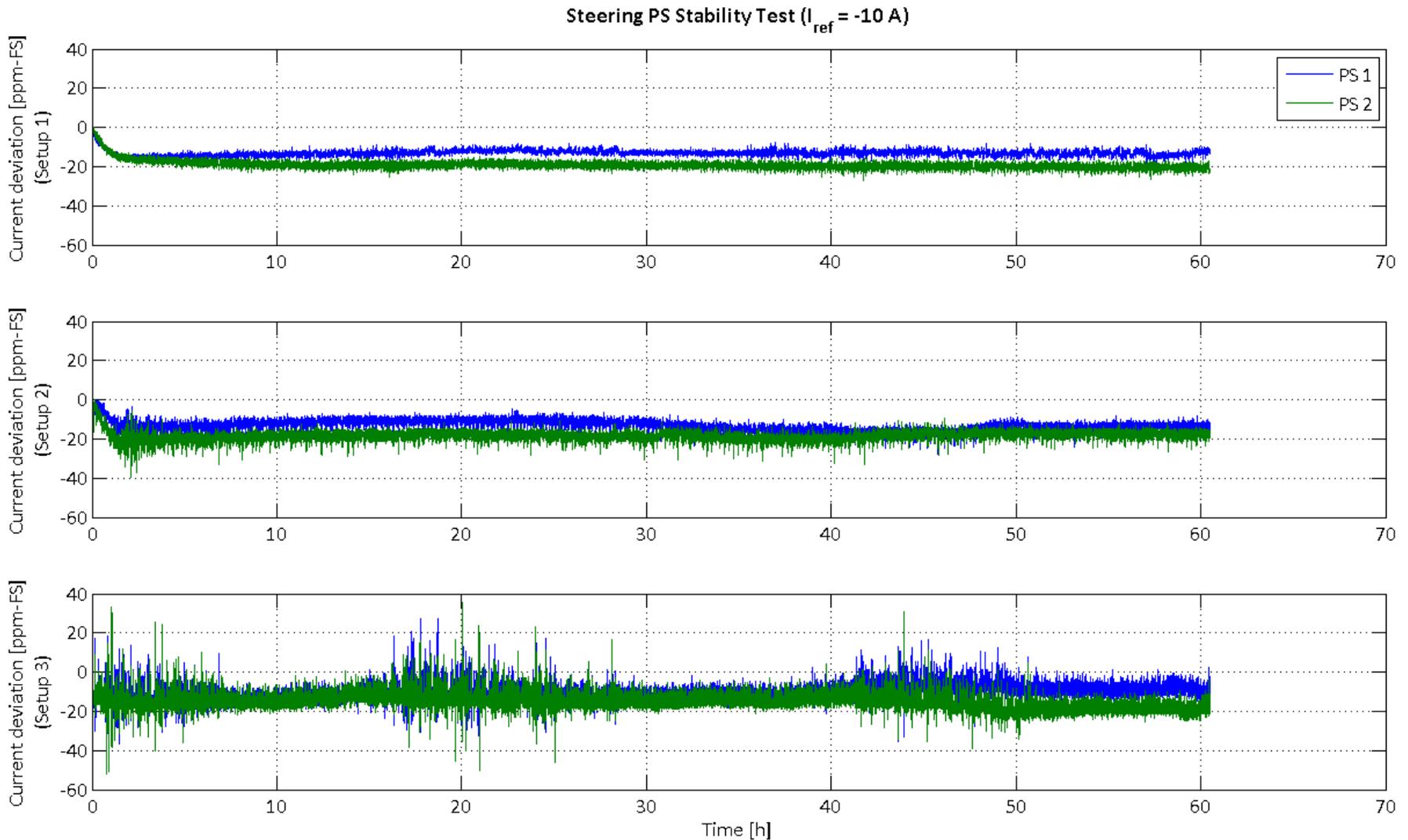
### Ripple RMS @ 10 Hz- 1 kHz



## LOW-POWER STABILITY ( $I_{OUT} = +10\text{ A}$ )



## LOW-POWER STABILITY ( $I_{OUT} = -10$ A)





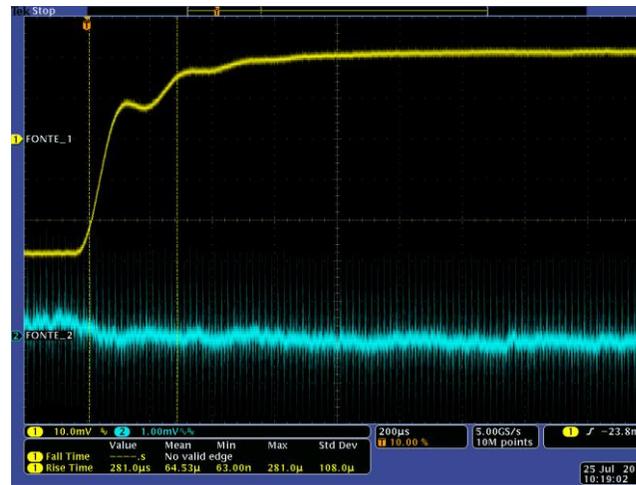
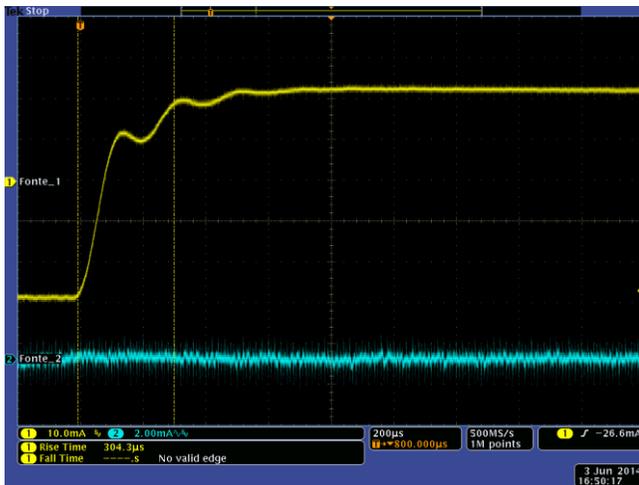
## LOW-POWER STEP RESPONSE

### Condition 1

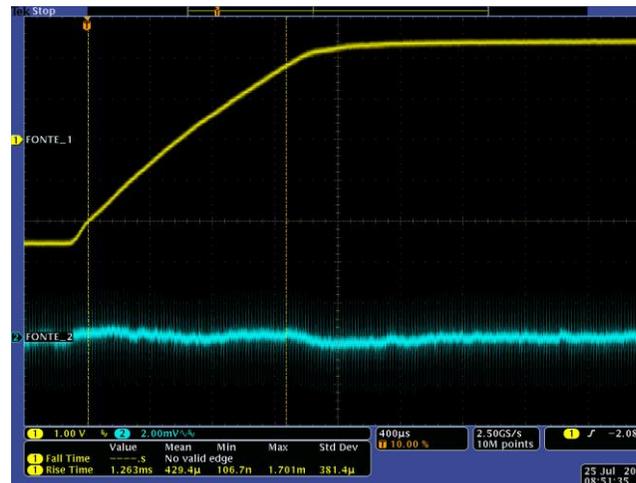
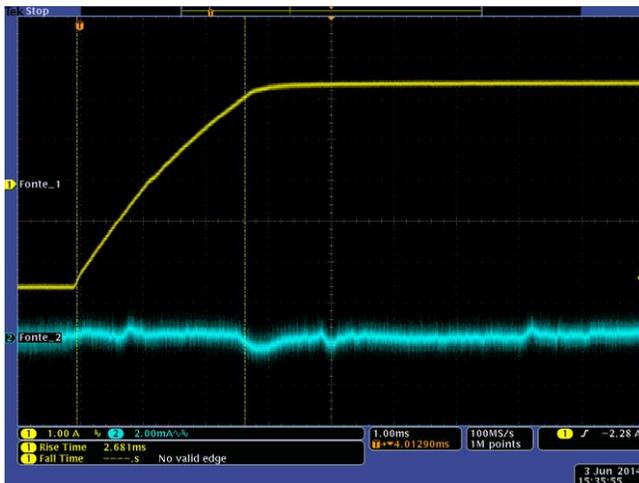
### Condition 2

### Condition 3

-25mA to +25mA



-2,5A to +2,5A

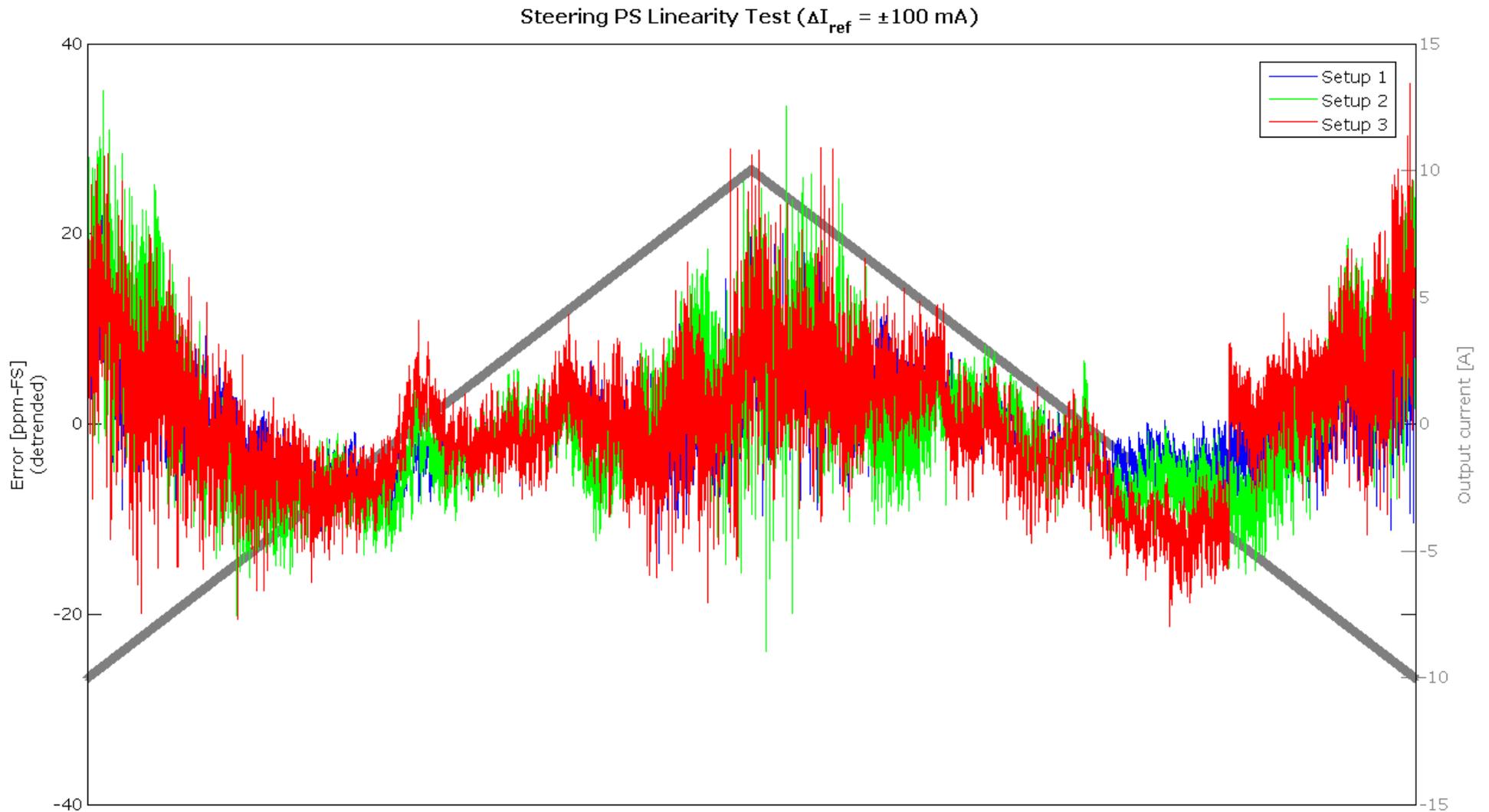


## LOW-POWER STEP RESPONSE

- For small-steps (50 mA), better than 500 us
- UVX storage ring corrector (w/ analog controller): 2 ms

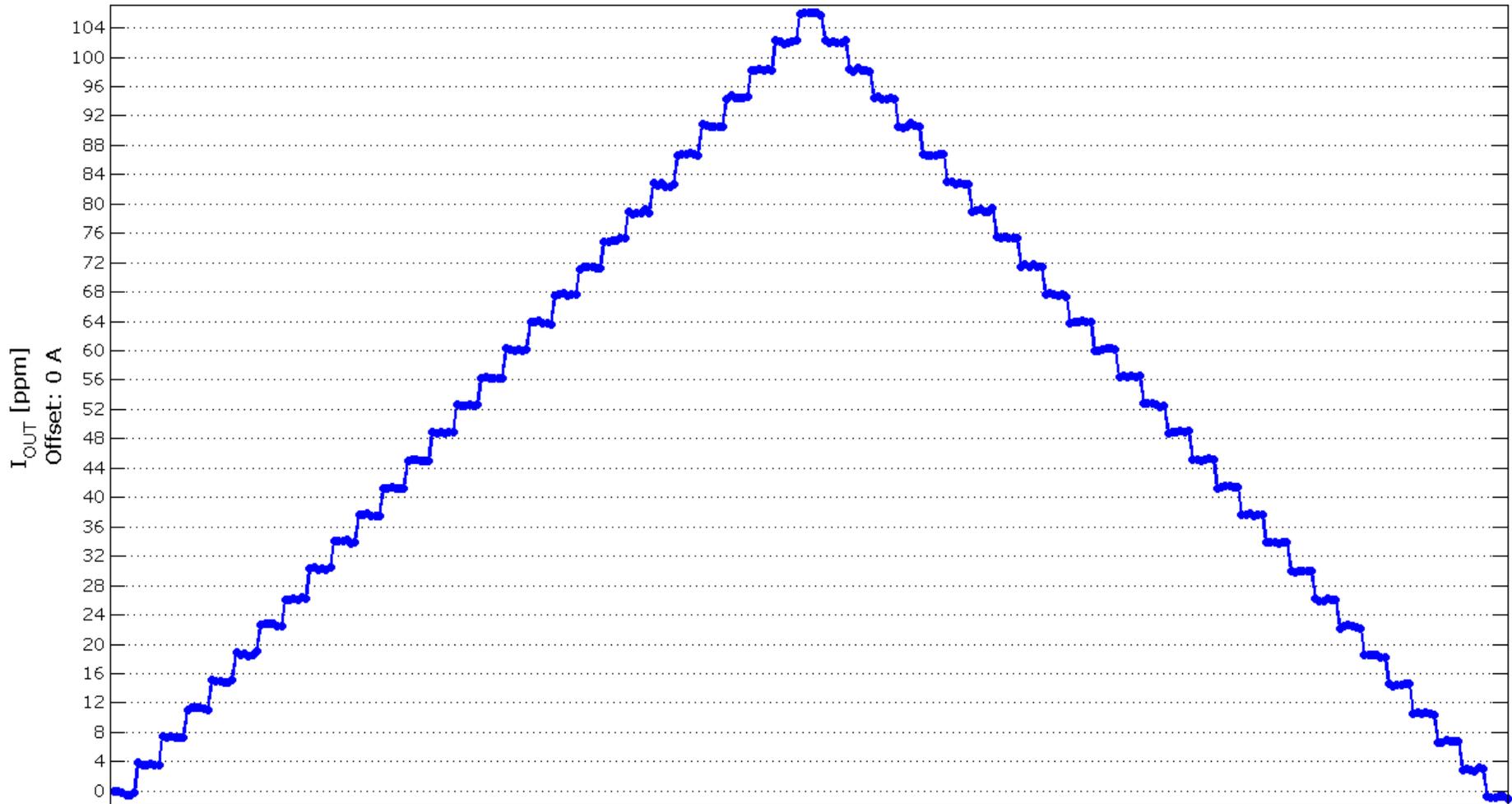
Step	Current change	Response Time[ms]			Current range	Response Time [ms]		
		Cond. 1	Cond. 2	Cond. 3		Cond. 1	Cond. 2	Cond. 3
5A	-2,5A a +2,5A	2,68	1,26	9,79	+2,5A a -2,5A	2,58	1,25	9,87
	+2,5A a +7,5A	5,61	2,26	22,79	+7,5A a +2,5A	1,34	0,78	5,10
	-7,5A a -2,5A	1,32	0,77	5,11	-2,5A a -7,5A	5,62	2,08	22,15
0,5A	-0,25A a +0,25A	0,39	0,28	0,99	+0,25A a -0,25A	0,43	0,28	1,03
	+4,75A a +5,25A	2,91	1,14	1,80	+5,25A a +4,75A	0,18	0,21	0,72
	-5,25A a -4,75A	0,14	0,24	0,74	-4,75A a -5,25A	2,76	2,60	1,72
50mA	-25mA a +25mA	0,30	0,28	0,50	+25mA a -25mA	0,29	0,26	0,46
	+0,975A a +1,025A	0,29	0,32	0,50	+1,025A a +0,975A	0,29	0,26	0,49
	-1,025A a -0,975A	0,29	0,26	0,49	-0,975A a -1,025A	0,34	0,29	0,48

## LOW-POWER LINEARITY (CONDITION 1)



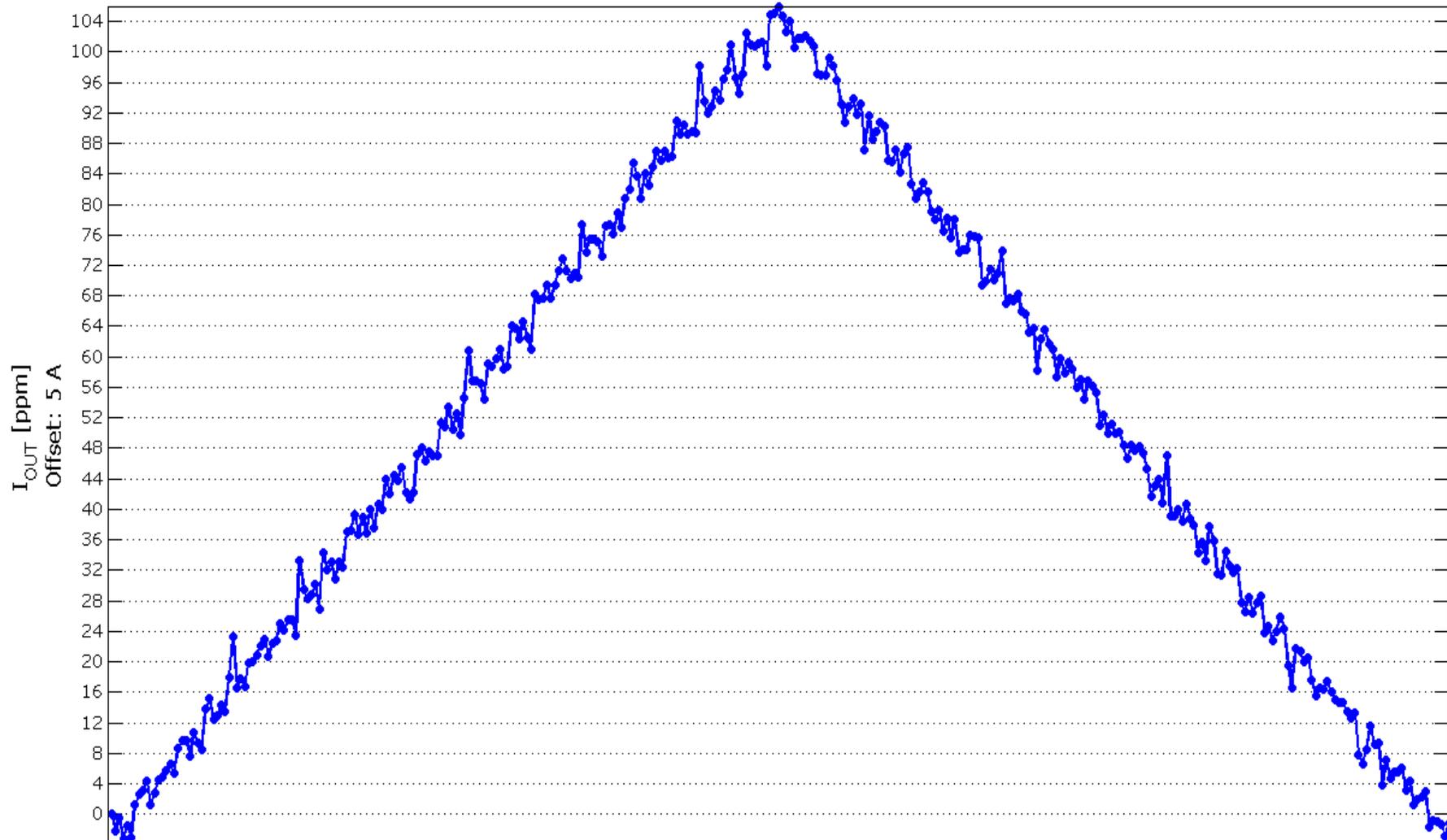
## LOW-POWER BIT INCREMENT (CONDITION 1)

Steering PS 18-bit Reference Current Increment ( $\Delta I_{ref} = 76.2 \mu A$ )



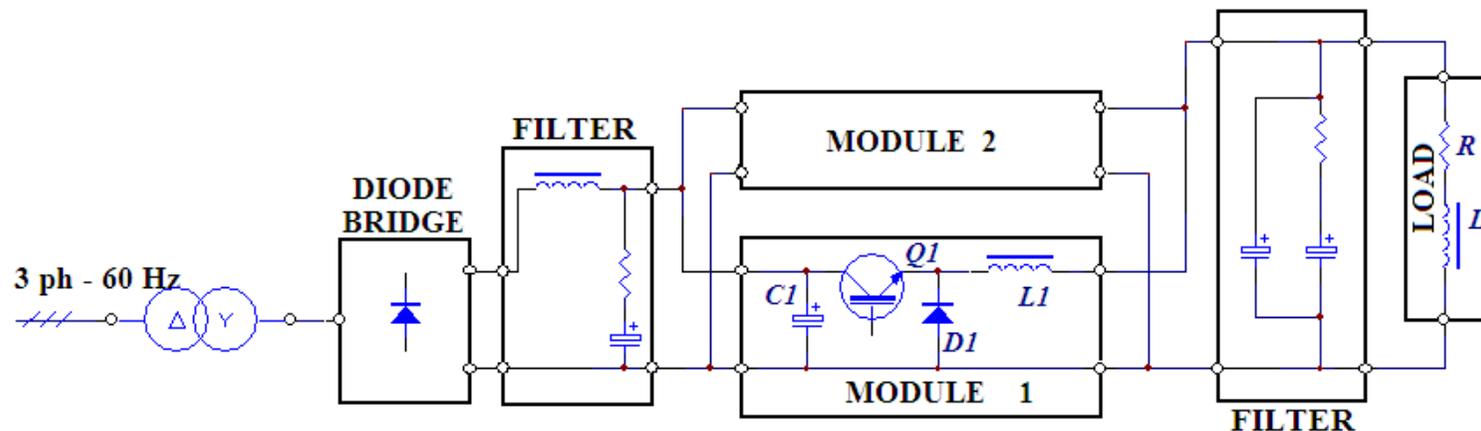
## LOW-POWER BIT INCREMENT (CONDITION 1)

Steering PS 18-bit Reference Current Increment ( $\Delta I_{ref} = 76.2 \mu A$ )



## HIGH-POWER 1<sup>ST</sup> PROTOTYPE

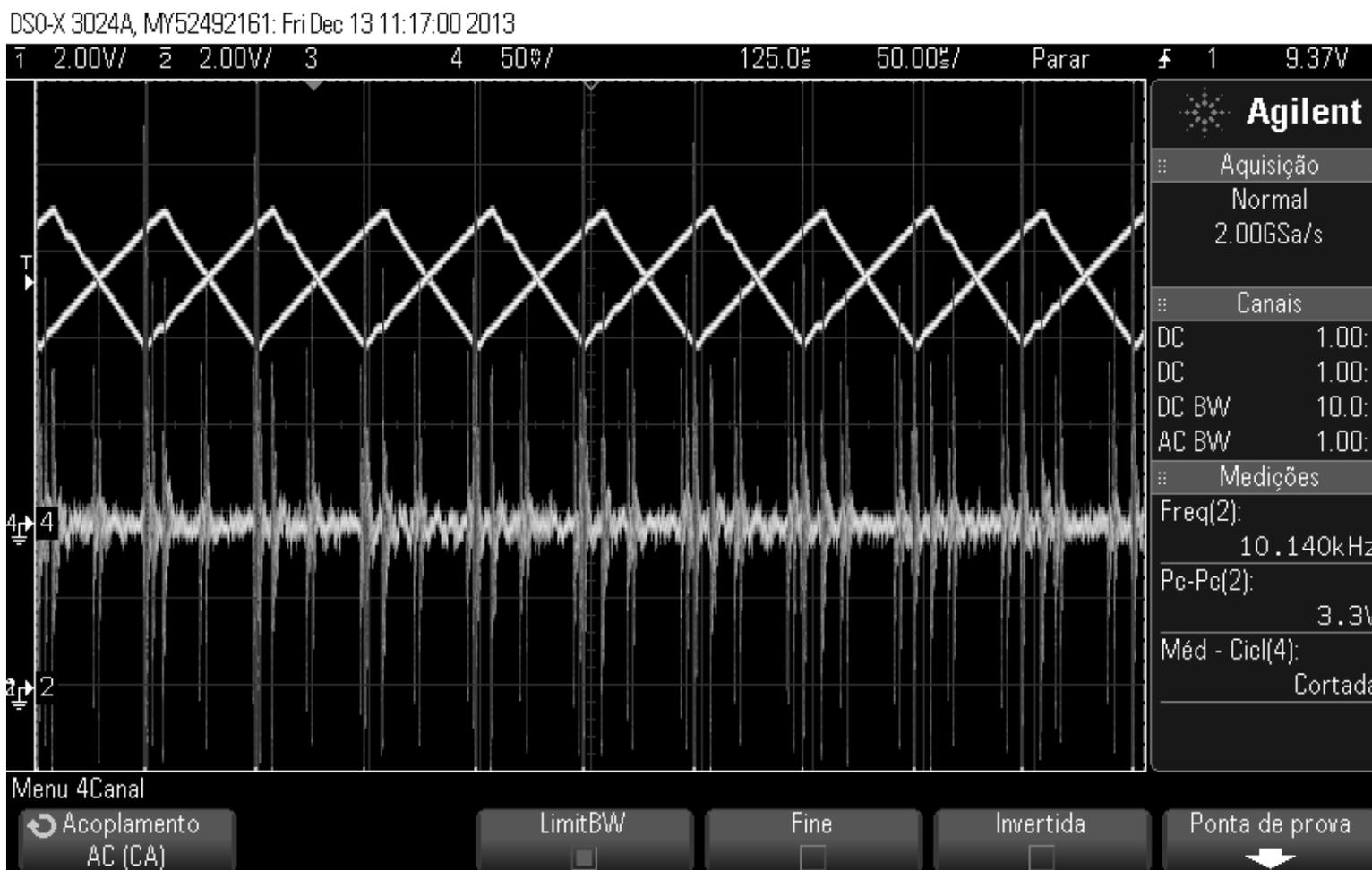
- 2 parallel switching modules with interleaved trigger
- 225 A / 22.5 V
- Natural cooling up to 100 W
- UVX quadrupole magnet
- Preliminary results with Low-Power supply as trim coils



## HIGH-POWER 1<sup>ST</sup> PROTOTYPE



## HIGH-POWER OUTPUT CURRENT WAVEFORMS (@ 225 A)



- Ch1 and Ch2: 1st and 2nd Module Current (24A/div)
- Ch4: AC Output Current (1.25A/div)
- Hor. Axis: 50us/div

## HP INTERFERENCE ON LP RIPPLE

- Significant increase of ripple with HP operation (@ 10 Hz – 1 kHz)

		FQ off		FQ @ 0A		FQ @ 112,5A		FQ @ 225A	
Iout [A]		mApp	uArms	mApp	uArms	mApp	uArms	mApp	uArms
DC-1MHz	-10	3,52	416	4,42	439	9,83	1352	16,63	2707
	-5	3,32	496	4,13	477	9,77	1358	15,51	2560
	0	2,64	277	3,78	293	9,53	1301	17,38	2705
	5	3,29	384	4,03	411	9,67	1328	16,94	2627
	10	3,37	413	4,24	417	10,07	1373	17,06	2743
10Hz-1kHz	-10	0,56	57	0,77	87	5,49	1102	16,34	2660
	-5	0,48	58	0,67	80	5,21	1064	10,69	2348
	0	0,40	52	0,61	73	5,26	1074	11,45	2497
	5	0,43	58	0,66	82	5,23	1066	10,98	2429
	10	0,53	62	0,78	90	5,44	1116	16,56	2822

## LP INTERFERENCE ON HP RIPPLE

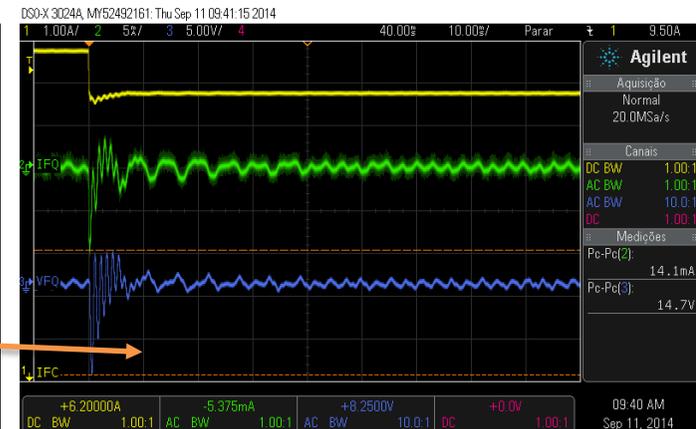
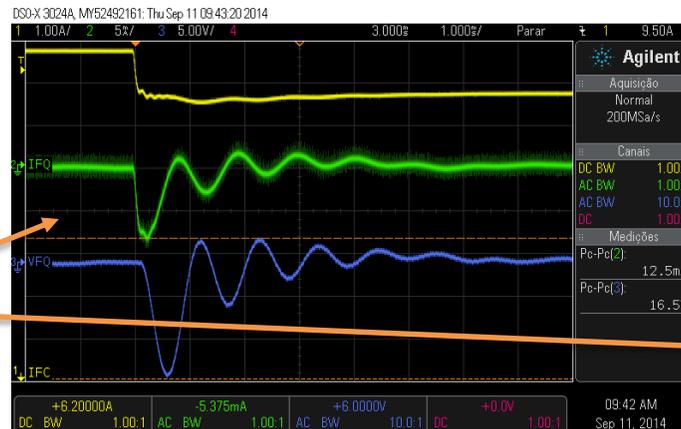
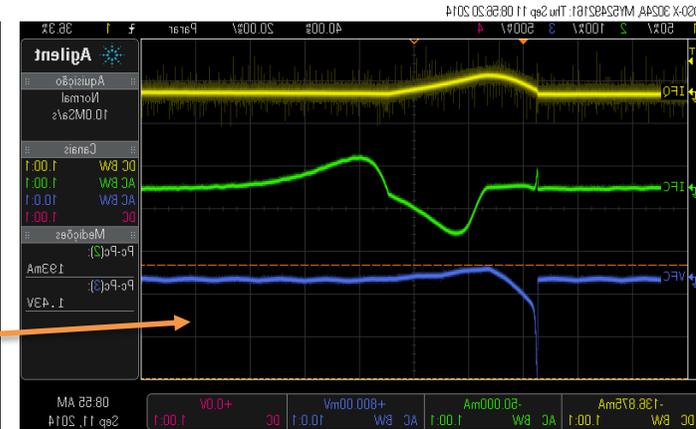
- Almost negligible, observed only on low currents and broadband

		FBP off		FBP @ 0A		FBP @ 5A		FBP @ 10A		
		Iout [A]	mApp	mArms	mApp	mArms	mApp	mArms	mApp	mArms
DC -	1MHz	0	73,0	1,78	67,3	1,87	68,4	2,17	68,3	2,60
		112,5	99,7	4,25	83,9	3,45	85,4	3,69	83,1	4,12
		225	103,8	7,79	80,6	7,08	83,7	7,04	82,1	7,31
10Hz -	1kHz	0	10,6	1,35	10,4	1,37	9,9	1,36	10,5	1,37
		112,5	23,0	2,54	19,4	2,64	20,2	2,63	19,9	2,66
		225	35,5	6,47	34,1	6,62	35,1	6,59	32,4	6,40

## STEP RESPONSE INTERFERENCE

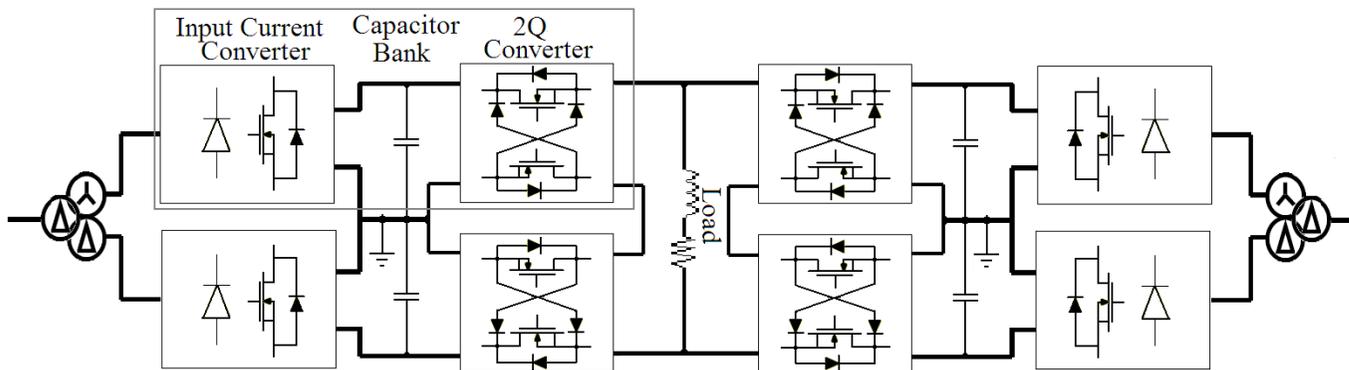
- Step applied on one PS, observation of disturbance on the other PS

	Step	DC current [A]	Current deviation [mA]
High-Power Step Current	0A - 100mA	0,0	54,0
		5,0	60,0
		10,0	193,0
	100 mA - 0A	0,0	9,4
		5,0	10,7
		10,0	72,0
Low-Power Step Current	0A - 10A	0,0	2530,0
	10A - 0A	0,0	3680,0
	9A - 10A	112,5	117,5
		225,0	107,5
	10A - 9A	112,5	312,5
		225,0	352,5



## AC POWER SUPPLY 1<sup>ST</sup> PROTOTYPE

- 1<sup>st</sup> Prototype built and being used by Magnet Group for testing QF prototype:
  - ✓ Maximum 130 A / 10 V following a sinusoidal wave
  - ✓ Maximum 70 ADC
  - ✓ Low effect of cycling in the grid
  - ✓ Still Analog Regulation

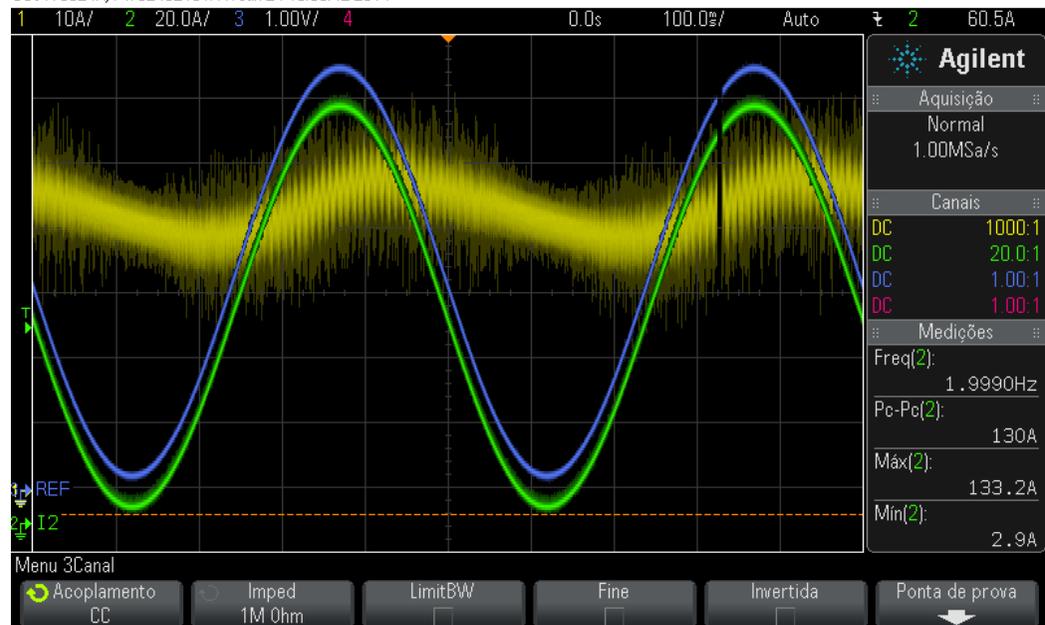


## AC POWER SUPPLY 1<sup>ST</sup> PROTOTYPE

Output Current Following a Sinusoidal  
Reference (4A to 130A, 2Hz)

Ch1: Input Current (10A/div); Ch2: Output Current (200A/div);  
Ch4: Input Reference (1V/div)

DSO-X 3024A, MY52492161: Fri Jan 24 10:06:42 2014



## Stability Test of Output Current @70A

